GALACTIC BULGES

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Section 1: Motivation and Scope of Review

§1.1 Introduction

In his introduction to the report of IAU Symposium # 1, *Coordination of Galactic Research*, held near Groningen, June 1953, Blauuw noted *'In the discussion the terms 'halo', 'nucleus' and 'disk' are used to indicate different parts of the Galaxy. These general regions are not defined more precisely. Their introduction proved very useful, and one might rather say that their more exact description is one of the problems of galactic research.'* This statement provides an excellent example of the limitations of terminology, and of the term *galactic bulge* in that this component continues to lack a clear definition (nucleus? halo?) of either its structure or its relationship to the other stellar components of the Galaxy. This is compounded by the difficulty of observing bulges even once one has decided which part of the galaxy that is.

The common usage of 'bulge', for example in the term 'bulge-to-disk ratio' allocates all 'non-disk' light in any galaxy which has a 'disk' into the 'bulge'. That is, the bulge contains any light that is in excess of an inward extrapolation of a constant scale-length exponential disk. Sandage (Carnegie Atlas of Galaxies, [Sandage & Bedke 1994]; panel S11 and p45) emphasises that 'One of the three classification criteria along the spiral sequence is the size of the central amorphous bulge, compared with the size of the disk. The bulge size, seen best in nearly edge-on galaxies, decreases progressively, while the current star formation rate and the geometrical entropy of the arm pattern increases, from early Sa to Sd, Sm and Im types.' This is the clearest convenient description of a 'bulge', namely a centrally-concentrated stellar distribution with an amorphous – smooth – appearance. Note that this implicitly excludes gas, dust, and continuing recent star formation by definition, ascribing all such phenomena in the central parts of a galaxy to the central disk, not to the bulge with which it cohabits. Further, for a bulge to be identified at all it must, by selection, have a central stellar surface density which is at least comparable to that of the disk, and/or it must have a (vertical) scale height which is at least not very much smaller than that of the disk. The fact that this working definition can be applied successfully to the extensive classifications in the Carnegie Atlas illustrates some fundamental correctness. It is also clear that bulges are very much a defining component whose properties underly the Hubble sequence, and hence the reason why we care – understanding how 'bulges' form and evolve is integral to the questions of galaxy formation and evolution.

This review considers the current wide-spread beliefs and preconceptions about 'Galactic Bulges' – for example, that they are old, metal-rich and related to elliptical galaxies – in the light of modern data. Our aim is to provide an overview of interesting and topical questions, and to emphasise recent and future observations that pertain to the understanding of the formation and evolutionary status of 'bulges'. We begin by considering some common preconceptions.

§1.2 Preconception Number 1: Bulges are Old.

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The expectation of 'old age' arose, as far as we can ascertain, from the interpretation of the observed correlation between stellar kinematics and metallicity for local stars in the Milky Way by Eggen, Lynden-Bell and Sandage (1962). These authors proposed a model of Galaxy formation by monolithic collapse of a galaxy-sized density perturbation, generalised to models wherein the spheroidal components of galaxies – including the entire stellar mass of an elliptical galaxy – formed stars *prior* to the dissipational settling to a disk, and so contained the oldest stars (e.g. review of Gott 1977). The high central surface brightness of bulges (and of ellipticals) also, assuming it corresponds to a high mass density, implies a higher redshift of formation, for a fixed collapse factor of the proto-galaxy, since at higher redshift the background density was higher (Peebles 1989).

There clearly is an older component in the central regions of the Milky Way Galaxy; the first real work on the bulge (or 'nucleus' as it was called at the time), used classical 'halo' tracers, such as globular clusters, RR Lyraes and Planetary Nebulae. Of course, one must remember that 'older' is used here in the sense in which that term was used until very recently, which meant much older than the local disk, which contains on-going star formation. That is, 'old' means 'there is no obvious AF star population'. The Baade-era concept of 'old' meant a turnoff in the F-region, which is of course old only for a very metal-poor system (see Sandage 1986, and the Carnegie Atlas for thorough reviews of Baade's Population concept). Further, the very idea of discriminating between ages of 10Gyr and 15Gyr is a recent concept, in spite of the large fractional difference.

Constraints on the redshift of formation of bulges can be obtained by direct observations of high-redshift galaxies, for which morphological information may be obtained with the Hubble Space Telescope (see §4). In general it is difficult to disentagle the effects of age and metallicity on stellar colours, even when the stars are resolved and colour-magnitude diagrams may be examined. The state-of-the art mean age determinations for lower redshift bulges and disks are discussed in (§3), while the interpretations of colour-magnitude diagrams are discussed in §2; much ambiguity and uncertainty remains.

Implicit in the Eggen, Lynden-Bell and Sandage (1962) scenario was the hypothesis that the Galactic bulge was simply the central region of the stellar halo, traced at the solar neighbourhood by the high-velocity subdwarfs. These stars are old by anyone's definition. Stellar haloes can be studied easily only in the Local Group, and we discuss the stellar populations in those galaxies in §2 below.

§1.3 Preconception Number 2: The Galactic Bulge is Super-Solar Metallicity

This belief was strongly supported by study of late M-giants in Baade's Window (cf. Frogel 1988), motivated by the Whitford (1978) paper comparing the spectrum of the Milky Way bulge to that of the integrated light of the central regions of external bulges and giant Elliptical galaxies (see Whitford 1986 for a personal interpretation of his research). Whitford's investigation aimed to determine whether or not the bulge of our galaxy was 'normal', i.e. the same as others. Whitford was apparently influenced, as were most people at that time, by the interpretation of the colour-magnitude relation of Faber (1973) to assume that bulges and ellipticals were differentiated only by luminosity, which determined the metallicity, and that ages were invariant, and *old*, with a turnoff

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mass of $\sim 1 M_\odot$ (Faber 1973), at least for the dominant population. In this case, the most metal-rich stars in a lower luminosity bulge, like that of the Milky Way, could be used as a template for the *typical* star in a giant elliptical.

Whitford (1978) concluded from his data that indeed 'the strengths of the spectral features in the sampled areas of the nuclear bulge of the Galaxy are very close to those expected from measures on similar areas of comparable galaxies.' However, Whitford's data were, by current standards, of low spectral resolution, and were limited to the following: spectra, with a resolution of 32Å in the blue, and 64Å in the red, for 3 regions in Baade's window and for the central regions of five edge-on spirals of type Sa to Sb; lower spectral resolution data for the central regions of M31; partial data - blue wavelengths only - for one elliptical (NGC3379, E1), and full wavelength coverage spectra for one other elliptical (NGC4976, E4) which he emphasised did not match the Milky Way, and was anomalous. Further, the data for Baade's window in the blue wavelength region – where direct comparison with a 'normal' elliptical galaxy was possible – were emphasised to be very uncertain, due to the large corrections for reddening and foreground (disk) emission. Thus, while the Whitford paper was deservedly influential in motivating comparison between stars in the Milky Way bulge and the integrated population of external galaxies, its detailed conclusions rest on rather poor foundations.

The results of Rich (1988), based on his low-resolution spectra, that the mean metallicity of K/M giants in Baade's Window was twice the solar value was very influential and widely accepted; however, it is now apparent that line-blending and elemental abundance variations contributed to a calibration error. We discuss below the current status of the metallicity–luminosity relation for bulges and for ellipticals, and the detailed chemical abundance distribution for stars in the bulge of the Milky Way; it is clear that while there do exist super-metal-rich stars in the bulge of the Milky Way, they are a minority, and their relationship to the majority population (are they the same age?) remains unknown.

§1.4 Preconception Number 3: Bulges are similar to elliptical galaxies

Bulges and ellipticals have traditionally been fit by the same surface brightness profiles, the de Vaucouleurs $R^{1/4}$ law; one is tempted for simplicity to assume that bulges are simply scaled-down ellipticals, and that they formed the same way. N-body simulations (e.g. van Albada 1982), together with analytic considerations of 'maximum entropy' endstates (Tremaine, Henon and Lynden-Bell 1986) suggested that this was through violent relaxation of a dissipationless, perhaps lumpy, system. These ideas incorporate the proposition (e.g. Toomre 1977; Barnes and Hernquist 1992) that equal-mass mergers destroy pre-existing stellar disks, and form bulges and ellipticals, these latter two being distinguished only by mass.

Further, the stellar kinematics of ellipticals and bulges of the same luminosity are similar, in that each rotates about as rapidly as predicted by isotropic oblate models (Davies *et al.* 1983). However, it is becoming clear that each of 'bulges' and 'ellipticals' is a somewhat heterogeneous classification, and may cover systems that formed in a variety of ways, as discussed below.

The above preconceptions may be tested against modern data. We proceed with the systems for which the most detailed data may be obtained, the galaxies in the Local Group, and then outward in distance.

Section 2 : Resolved Bulges – Local Group Galaxies

The Local Group provides a sample of bulges in which one can determine the stellar distribution functions on a star-by-star basis, allowing a more detailed analysis than is possible based on the integrated properties of more distant bulges/haloes. In this comparison, one must be careful to isolate the essential features, since there is much confusing detail, both observational and theoretical, specific to individual galaxies.

Obvious questions which can be addressed most efficiently locally include possible differences or similarities or smooth(?) gradients in properties – kinematics, chemical abundance distribution, age distribution, scale-lengths, profiles etc – from inner 'bulges' to outer 'haloes', and from 'bulges' to inner disks. Different tracers can be used, allowing comparisons between e.g. globular clusters and field stars.

§2.1 **Milky Way Galaxy**

Let us adopt for the moment the working definition of 'the bulge' as the component constituting the amorphous stellar light in the central regions of the Milky Way. While one might imagine that the Milky Way bulge can be studied in significantly more detail than is possible in other galaxies, our location in the disk restricts our view such that this is true only several kpc from the Galactic centre. Most of the Galactic bulge is obscured by dust and stars associated with the foreground disk. We illustrate the situation in Figure 1 below.

Figure 1 here: a full page, landscape image

§2.1.1 Chemical Abundances

Chemical abundances of K- and M-giants in the central regions of the Galaxy have been determined by a variety of techniques, ranging from high-resolution spectra allowing elemental abundance analyses, to intermediate-band photometry. Application to Baade's window – approximately 500 pc projected distance from the Galactic center – determined that the metallicity distribution function (calibrated onto a [Fe/H] scale) of K/M giants is broad, with a maximum at ~ -0.2 dex (i.e. ~ 0.6 of the solar iron abundance) and extending down to at least -1 dex and up to at least $+0.5$ dex (e.g. McWilliam and Rich 1994; Sadler, Rich and Terndrup 1996). It remains unclear to what extent these upper and lower limits are a true representation of the underlying distribution function and to what extent they are observational bias, set by calibration difficulties and/or sensitivities of the techniques. Further, the identification of foreground disk stars remains difficult.

At larger Galactocentric distances, Ibata and Gilmore (1995a,b) utilised fibre spectroscopy down many lines-of-sight to mimic 'long-slit spectroscopy' of the Galactic Bulge, in order to facilitate a direct comparison between the Milky Way bulge and those of external spiral galaxies. They obtained spectra of ~ 2000 stars; star count models, stellar

luminosity classifications and kinematics were used to isolate ~ 1500 K/M-giants from 700 pc to 3.5 kpc (projected distance) from the Galactic Center. These authors estimated metallicities from the Mg'b' index, calibrated against local field stars; thus there is a possible zero-point offset of up to ~ 0.3 dex, dependent on the element ratios of the Bulge stars compared to the local stars. They truncated their distribution function above the solar value, due to the great similarity in low-resolution spectra between foreground K dwarfs and such metal-rich K giants, which leads to an inability to identify contamination of the bulge sample by disk stars. The find that the outer bulge metallicity distribution function peaks at ~ -0.3 dex, and continues down beyond -1 dex (see Figure 2 below).

Minniti *et al.* (1995) present the metallicity distribution function for ~ 250 K/M-giants in two fields at projected Galactocentric distances of $R \sim 1.5$ kpc. Their results are calibrated only for stars more metal-poor than ~ -0.5 dex, and one of their fields was selected with a bias against high metallicities. Their data for their unbiased field again shows a broad distribution function, approximately flat from -1 dex to $+0.3$ dex. Minniti *et al.* (1995) also summarize (and list the references to) results from extant photometric chemical abundance determinations (e.g. Morrison and Harding 1993); in general these agree neither with each other, nor with spectroscopic determinations. Further work is clearly needed.

The few large scale kinematic surveys of the bulge (Ibata and Gilmore 1995a,b; Minniti *et al.* 1995) find no convincing evidence for an abundance-kinematics correlation within the bulge itself, after corrections for halo stars and disk stars (see also Minniti 1996).

The most striking aspects of the metallicity distribution function of K/M giants in the bulge are its width, and the fact that there is little if any radial gradient in its peak (modal) value, when one considers only spectroscopic determinations. Further data are required to determine whether or not the wings of the distribution are also invariant. Certainly the very late spectral-type M-giants have a significantly smaller scale-height than do the K-giants (Blanco and Terndrup 1989), a fact that could be a manifestation of either a metallicity gradient in the high-metallicity tail of the distribution function, or of an age gradient, with a small scale-height, metal-rich, younger population being concentrated to the Galactic Plane. It is clear that star formation occurs in the very center of the Galaxy (e.g. Gredel 1996) so that the meaning of a distinction between inner disk and bulge stellar populations remains problematic, and perhaps semantic, in the inner few hundred parsecs of the Galaxy. External disk galaxies do show colour gradients in their bulge components, but the amplitude is luminosity-dependent and expected to be small for bulges like that of the Milky Way (Balcells and Peletier 1994).

The little evidence there is concerning the stellar metallicity distribution of older stars in the inner disk is also somewhat confusing. An abundance gradient with the mean rising ~ 0.1 dex/kpc towards the inner Galaxy, but for data only relevant to Galactocentric distances of 4–11 kpc, is plausibly established for F/G stars of ages up to 10^{10}yr (Edvardsson *et al.* 1993; their Table 14 – their few older stars show no evidence for a gradient). A similar amplitude of metallicity gradient is seen in open clusters older than 1 Gyr, but

for data exterior to the solar circle (e.g. Friel 1995). Earlier data for K giants however suggests no radial abundance gradient, with a mean [Fe/H]~ -0.3 from exterior to the Sun to within 1 kpc of the center (Lewis and Freeman 1989), even though such stars should be no older than the F/G sample. Clearly, however, the abundance range which contains most of the bulge stars overlaps that of the disk, with probable disk gradients being smaller than the range of the bulge metallicity distribution function. This is of especial interest given the correlations, discussed below, between the colours of bulges and inner disks in external galaxies (de Jong 1996; Peletier and Balcells 1996).

As discussed further below, the mean metallicity of field bulge stars is significantly above that of the globular cluster system of the Milky Way, even if only the inner, more metal-rich 'disk' globular clusters, with mean metallicity of ~ -0.7 dex (e.g. Armandroff 1989) are considered.

Fig 2 here

A characterisation of the width of the metallicity distribution comes from the fact that the distributions for both Baade's window (Rich 1990) and for the outer bulge (Ibata and Gilmore 1995b) are consistent with the predictions of the 'Simple Closed Box' model of chemical evolution. This is in contrast to the disk of the Milky Way, at least in the solar neighbourhood, which has a significantly narrower metallicity distribution, and indeed a shortage of low-metallicity stars compared to this model (the 'G-Dwarf problem'). This of course does *not* mean that any or all of the assumptions inherent in the simple closed box model were realised during bulge formation and evolution, but is rather a way of quantifying the greater width of the observed metallicity distribution in the bulge compared to the disk at the solar neighbourhood, two locations which have the same *mean* metallicity.

Elemental abundances provide significantly more information than do 'metallicity' since different elements are synthesised by stars of different masses and hence on different timescales (e.g. Tinsley 1980). Different scenarios for the formation of the bulge could in principle be distinguished by their signatures in the pattern of element ratios (Wyse and Gilmore 1992). The available data are somewhat difficult to interpret, in part due to small number statistics (e.g. McWilliam and Rich 1994; Sadler, Rich & Terndrup 1996) but this can be rectified with the coming 8–10m class telescopes.

§2.1.2 Age Estimates

RR Lyrae stars, traditional tracers of an old, metal-poor population, are found in significant numbers along 'bulge' lines-of-sight, at characteristic distances which place them close to the Galactic Center (Oort and Plaut 1975). This has been taken as supporting evidence for an old bulge; indeed Lee (1992) argued that for a stellar population of a high mean metallicity, such as that of the bulge discussed above, to produce significant numbers of RR Lyrae stars (from the metal-poor tail of the chemical abundance distribution), it must be older than a metal-poor population with the same RR Lyrae production rate. Lee hence concluded that the bulge contained the oldest stars in the Galaxy, older than the stars in the field halo. But are the observed RR Lyrae stars indeed part of the metal-rich

bulge, or of the metal-poor stellar halo, whose density of course also peaks in the inner Galaxy?

The samples of RR Lyraes available for this experiment have been small. However, a side-benefit of the recent interest in microlensing surveys of the Galactic bulge (e.g. OGLE; MACHO; DUO) has been well-defined catalogs of variable stars, including RR Lyraes. In an analysis of the projected spatial distribution of DUO RRLyraes, segregated statistically by metallicity based on periods, and fitting to density laws of halo, disk, and bulge, Alard (1996) has found that the great majority of RR Lyrae stars in his catalog are *not* associated with the bulge, but rather with the thick disk and halo. Nonetheless, a detectable fraction of the most metal-rich RR Lyrae variables of the 1400 discovered by DUO do indeed belong to a concentrated bulge population. These stars comprise only about 7 percent of the whole RR Lyrae sample. Thus it is likely that the microlensing surveys have in fact made the first discovery of true bulge RR Lyraes. The intermediate abundance RR Lyraes are primarily thick disk, while the most metal poor are primarily halo, from this analysis.

Analysis of the variable stars detected by the IRAS satellite (mostly Mira variables) implied a significant intermediate-age population (e.g. Harmon and Gilmore 1988), perhaps that traced by the carbon stars (Azzopardi *et al.* 1988; Westerlund *et al.* 1991) and the strong red clump population (e.g. Pacynski et al 1994a,b).

Renzini (1995) has emphasised that the relative strength of the red clump and red giant branches is dependent on helium content as well as on age, and should the bulge stars be of high helium content – as expected if they were super-metal-rich – then the observed red clump could still be consistent with an old age. However, the fact that the mean metallicity of the bulge is now established, from unbiased tracers, to be below the solar value, with a correspondingly much reduced helium abundance, makes this unlikely, and supports intermediate age as the explanation.

Understanding the effects of dust along the line-of-sight to the central regions is crucial. The analysis of IR data reduces some of the reddening problems of optical data, but again the interpretation in terms of stellar properties is far from unambiguous. Houdashelt (1996) concluded that a typical age of perhaps 8 Gyr, and mean metallicity of [Fe/H]$\sim$ -0.3 (adopted from the spectroscopic results discussed above) was consistent with his IR photometry and spectroscopy for stars in Baade's window.

Optical/near-IR colour-magnitude diagrams which extend well below the main sequence turnoff region may be used to make quantitative statements about mean age and age ranges of stellar populations, modulo uncertainties in this case due to large and highly variable extinction, to extreme crowding in the inner fields, and to the contribution of foreground stars. In spite of these complications Ortolani *et al.* (1995) concluded, on the basis of a comparison of HST colour-magnitude data for the horizontal branch luminosity functions of an inner globular cluster and ground-based data towards Baade's window, that the stellar population of the bulge is as old as is the globular cluster system, and further shows negligible age range. This contrasts with earlier conclusions based on pre-refurbishment

HST colour-magnitude data for Baade's Window (Holtzman *et al.* 1993), suggesting a dominant intermediate-age population. Future improved deep HST colour-magnitude data are eagerly awaited.

An example of the information which can be obtained is given in Figure 3, which is a V–I, V colour-magnitude diagram from WFPC2 data (planetary camera) obtained as part of the Medium Deep Survey (S. Feltzing, private communication).

fig 3 here

§2.1.3 Bulge Structure

The only single-parameter global fit to the surface brightness of the combined halo plus bulge of the Galaxy, implicitly assuming they are a single entity, is that by de Vaucouleurs and Pence (1978). From their rather limited data on the visual surface brightness profile of the bulge/halo interior to the solar Galacto-centric distance, assuming an $R^{1/4}$-law profile, they derived a projected effective radius of 2.75 kpc, which may be de-projected to a physical half-light radius of 3.75 kpc. As shown by Morrison (1993), the de Vaucouleurs and Pence density profile, extrapolated to the solar neighbourhood, is brighter than the observed local surface brightness of the metal-poor halo, obtained from star counts, by 2.5 magnitudes. Since the density profile of the outer halo is well described by a power law in density, with index $\rho(r) \propto r^{-3.2}$, and oblate spheroidal axis ratio of about 0.6 (Larsen and Humphreys 1994; Wyse and Gilmore 1989), this result actually provides the first, though unappreciated, evidence that the central regions of the galaxy are predominantly bulge light, and that the bulge light falls off faster than does the outer halo light. That is, the bulge and halo are not a single structural entity. More generally, since the spatial density distribution of the stellar metal-poor halo is well described by a power law, while the inner bulge (see below) is well described by another power-law of much smaller scale length, the apparent fit of the single $R^{1/4}$-law profile must be spurious and misleading.

The limiting factors in all studies of the large-scale structure of the stellar Galactic bulge are the reddening, which is extreme and patchy, and severe crowding. The systematic difference between the best pre-HST photometry in crowded regions and the reality, as seen by HST, is now well appreciated after many studies of globular clusters. Near IR studies within a few degrees of the Galactic Plane show optical extinction which has a random variation, on angular scales down to a few arcseconds, of up to $A_V \sim 35$ mag (e.g. Catchpole, Whitelock and Glass 1990). At southern Galactic latitudes however, more than a few degrees from the plane, extinction is both low (typically $E_{B-V} \sim 0.2$) and surprisingly uniform, as is evident in the optical bulge image in Figure 1, and as exploited by Baade. Nonetheless, detailed star-count modelling of the inner galaxy (Ibata and Gilmore 1995a,b; M. Unavane private communication) demonstrates that extinction variations are still larger, in their photometric effects, than are the photometric signatures of different plausible structural models. This sensitivity to extinction, together with the extreme crowding which bedevils ground-based photometry, is well illustrated by the recent history of structural analyses of the inner Milky Way disk by the OGLE microlensing group, based on low spatial-resolution optical data. Their initial analysis of their data suggested that there is no inner disk in the Galaxy, only prominent foreground spiral structure

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(Paczynski *et al.* 1994a). After more careful consideration of crowding, and of alternative extinction models, this detection of a 'hole' in the disk was retracted (Kiraga *et al.* 1997). The true spatial density distribution of the inner disk remains obscure.

There are many analyses of the surface brightness structure of the bulge, ranging from straightforward counts of late-type stars down the minor axis (cf. Frogel 1988 for references) through extensive 2-D analyses (Kent, Dame and Fazio 1991), to detailed inversions of photometric maps (e.g. Blitz and Spergel 1991; Binney, Gerhard and Spergel 1997). In all such cases extreme reddening near the plane precludes reliable use of low spatial resolution data with $|b| < 2$, irrespective of the techniques used. The zeroth order properties of the photometric structure of the bulge are fairly consistently derived in all such studies, and determine ~ 350 pc for the minor axis exponential scale height, and significant flattening, with minor:major axis ratio of ~ 0.5. Together with a disk scale-length of around 3 kpc, this result places the Milky Way Galaxy within the scatter of late-type disk galaxies on the correlation between disk and bulge scale-lengths of Courteau de Jong and Broeils (1996).

Considerable efforts have been expended in the last decade to determine the 3-dimensional structure of the Galactic bulge. These efforts began at a serious level with analyses of the kinematics of gas in the inner Galaxy, following the prescient work of Liszt and Burton in the 1980s (see Liszt and Burton 1996, and Burton, Hartmann and West 1996 for recent reviews, and introductions to the subject), of Gerhard and Vietri (1986) together with much other work reviewed by Combes (1991). A resurgence of interest in bar models has been motivated in part by new dynamical analyses (e.g. Binney *et al.* 1991; Blitz *et al.* 1993), in part by the realisation that near-IR data might reflect the pronounced molecular gas asymmetry (Blitz and Spergel 1991), in part by gravitational microlensing results (Paczynski *et al.* 1994b), and in part by the new photometric COBE/DIRBE data (Weiland *et al.* 1994).

It appears that all galaxies in their central regions have non-axisymmetric structures, often multiple structures such as bars within bars (e.g. Shaw *et al.* 1995; Friedli *et al.* 1996). The distinction between inner spiral arms, bars, lenses, local star formation, and such like is perhaps of semantic interest except in cases where the distortions are of large amplitude, such as to affect the dynamical evolution. Is the Galaxy like that? The significant question is the existence of a substantial perturbation to the inner density distribution, and gravitational potential, associated with a bar. Secondary questions are the shape of that bar, and its relationship to the disk or to the bulge. The extant 3-dimensional models of the central regions of the Milky Way derived from the COBE surface photometry depend on systematic asymmetries of the derived 'dust-free' surface brightness with longitude of less that 0.4 magnitudes in amplitude, after statistical correction for extinction which is locally some orders of magnitude larger in amplitude (Binney, Gerhard and Spergel 1997). Thus they are crucially sensitive to reddening corrections made on a scale of 1.5 degrees (the COBE/DIRBE resolution) although reddening varies on much smaller scales (Fig 1).

The models also provide only a smooth description of most of the known foreground disk structure such as can be seen in Figure 1 – the Ophiuchus star formation region, the Sagittarius spiral arm, etc. – and do not work at low Galactic latitudes. This model disk must be subtracted before bulge parameters can be derived. The best available description of the stellar bulge derived this way suggests axis ratios $x : y : z \sim 1.0 : 0.6 : 0.4$ (Binney, Gerhard and Spergel 1997). This is a rather mild bar.

It is worth noting that this model, while the best currently available, fails to explain either the high spatial frequency structure in the photometric data, or the observed gravitational microlensing rate towards the inner Galaxy (Bissantz, Englmaier, Binney and Gerhard 1997, in addition to having remaining difficulties with the details of the gas kinematics in the inner Galaxy. Further, there is little evidence for non-axisymmetry in the potential from analyses of stellar kinematics – radial velocity surveys find consistency with an isotropic oblate rotator model (e.g. Ibata and Gilmore 1995; Minniti 1996). Although evidence for a weak bar is seen in proper-motion surveys, this is very dependent on the distances assigned to the stars (Zhao, Rich and Spergel 1994). Thus it must be emphasised that the best available models for the inner Galaxy remain poor descriptors of the very complex kinematics and spatial distribution of the gas (see Liszt and Burton 1996), and of the complex kinematics of some samples of stars (e.g. Izumiura *et al.* 1995).

Analysis of the photometric structure of the inner galaxy is a very active field of research, promising major progress in the next few years with the availability of the Infrared Space Observatory imaging survey data of the inner galaxy (Perault *et al.* 1996). ISO improves on the $\sim 1°$ spatial resolution of COBE, having typically 6arcsec resolution in surveys. These data for the first time provide a detailed census of individual stars and the ISM in the inner Galaxy, with sufficient resolution and sensitivity to see single stars at the Galactic centre, thereby allowing the first ever determination of the true 3-dimensional spatial distribution of the inner Galaxy.

We consider the kinematics of the Galactic bulge, the halo and the disk, and their implications for formation models, further below (section 5).

Section 2.2 M33 (NGC 598)

The stellar population of M 33 was reviewed by van den Bergh (1991a) where the reader is referred for details. We discuss the significant developments since then concerning the existence and nature of the stellar halo and bulge.

M33 shows photometric evidence for non-disk light, in particular in the central regions, but there remains uncertainty as to the nature of this light, and indeed whether or not there is a central bulge component, distinct from the stellar halo.

Attempts to fit optical and IR data for the central regions with an $R^{1/4}$ law generally agree with a 'bulge-to-disk' ratio of only $\sim 2\%$, or $M_{V,bulge}$ fainter than ~ -15 (Bothun 1992; Regan and Vogel 1994). Regan and Vogel emphasise that a single $R^{1/4}$ provided the best fit to their data. There is some evidence from ground-based H-band imaging (Minnitti, Olszewski and Rieke 1993) and from HST V−I/I CMD data (Mighell and Rich 1995) for AGB stars in the central regions, in excess of the number predicted by a simple

extrapolation from the outer disk; these stars have been ascribed to a young-ish centrally-concentrated bulge. However, McLean and Liu (1996) contend that their JHK photometry, after removal of crowded regions, shows no resolved bulge population distinct from the smooth continuation of the inner disk.

Is the $R^{1/4}$ component metal-poor or metal-rich? The giant branch of the HST CMD data is consistent with a broad range of metallicity, ranging from M15-like to 47Tuc-like, some 1.5 dex in metallicity. The low end of this metallicity range is consistent with that estimated earlier from ground-based CMD data for fields in the outer 'halo', [Fe/H] ~ -2.2 (Mould and Kristian 1986). These outer fields showed a narrow giant branch, consistent with a small dispersion in metallicity, and thus the two datasets together are suggestive of a gradient in the mean metallicity and metallicity dispersion. This may be interpreted as evidence for a centrally-concentrated more metal-rich component, albeit following the same density profile as the metal-poor stars.

Pritchett (1988) reported a preliminary detection of RR Lyrae stars in M33, again evidence for old, probably metal-poor, stars.

The semi-stellar nucleus of M33 has a luminosity similar to that of the brightest Galactic globular clusters, $M_V \sim -10$, and a diameter of ~ 6 pc. Analysis of its spectrum (Schmidt, Bica and Alloin 1990) demonstrated that its blue colour reflects the presence of young stars (age less than 1 Gyr) rather than extremely low metallicity; old and intermediate-age stars with metallicity greater than 0.1 of the solar value dominate. The relation of this nucleus to the 'bulge', if any, is unclear.

The only kinematic data for non-disk tracers in M33 are for a subset of its ~ 200 'large clusters of concentrated morphology' (Christian 1993) of which perhaps 10% have the colours of the classical old globular clusters of the Milky Way. Fourteen of these clusters have kinematics suggestive of being 'halo' objects, in that they define a system with little net rotation, and with a 'hot' velocity dispersion of order $1/\sqrt{2}$ times the amplitude of the HI rotation curve (Schommer *et al.* 1991; Schommer 1993). Estimates of the metallicities and ages of the 'populous' clusters, based on spectrophotometry, suggest a wide range of each, with even the 'globular clusters' spanning perhaps ~ -2 dex to just under solar metallicity (Christian 1993). Improved estimates from better data are possible and desirable. M33 has a very large number of globular clusters per unit field halo light, but the meaning of this is unclear.

In summary, M33 has a low luminosity 'halo', which is at least in part old and metal poor. There is no convincing evidence for the existence of a bulge in addition to this halo.

Section 2.3 M31 (NGC 224)

The stellar population of M 31 was reviewed by van den Bergh (1991b) and again we restrict discussion to significant subsequent developments.

The field non-disk population has been studied by several groups, following Mould and Kristian (1986; see also Crotts 1986). These authors established, from V and I data reaching several magnitudes down the giant branch, that the bulge/halo of M31, at 7 kpc from center, has mean metallicity like the Galactic globular 47 Tuc, [Fe/H] ~ -0.7, and a

significant dispersion in metallicity, assuming an old population, down to ~ -2 dex and up towards solar. Similar conclusions have been reached from HST data for the outer regions of M31 (~ 10 kpc) by Holland, Fahlman and Richer (1996), and by Rich *et al.* (1996) at ~ 30 kpc from the centre, limiting the amplitude of any chemical abundance gradients.

These HST data also established firmly the lack of Blue Horizontal Branch stars in the halo of M31, confirming the suggestion by Pritchet and van den Bergh (1987; 1988). The horizontal branch (HB) morphology is apparently too red for the mean metallicity, assuming that the HB traces a population as old as the Galactic halo globular clusters, so that the M31 field suffers a severe 'second-parameter problem'. Age can affect HB morphology, in that younger populations are redder at a given metallicity, other things being equal, (e.g. Lee 1993, who also demonstrates the effects of many other parameters), so that it is of interest to consider this possibility (while recalling that Richer *et al.* (1996) argue quite convincingly, based on relative ages for those Galactic globular clusters with main sequence turn-off photometry, that age is *not* the dominant 'second parameter' of HB morphology, at least in these systems). Indeed, the presence of bright stars, identified as intermediate-age AGB stars, has been suggested from (pre-refurbishment) WF/PC HST VI data at least within the inner two kiloparsecs of the bulge (Rich and Mighell 1995). Morris *et al.* (1994) argued for a ubiquitous strong luminous AGB component, with a typical age of 5 Gyr, from their ground-based V and I data reaching the bright giants in various fields of M31, 16–35 kpc along the major axis of the disk and one probing the halo at 8 kpc down the minor axis (close to the field of Mould and Kristian 1986). Rich *et al.* (1996), and also Holland, Fahlman and Richer (1996), find no evidence for an extended giant branch in their WFPC2 HST data for fields in the outer halo, at 10–30 kpc from center, where again the RHB/clump is dominant, with essentially no trace of a BHB. Thus the data describing possible metallicity/age effects remain unclear.

Large-scale surface photometry of the disk and of the bulge of M31, in many broadband colours, was obtained and analysed by Walterbos and Kennicutt (1988). They found that there was no colour gradient in the bulge, and that the inner disk and the bulge have essentially the same colours, being those of 'old, metal-rich stellar populations'. This similarity of broad-band colours has subsequently been found for a large sample of external disk galaxies, as discussed in §3, and clearly must be incorporated into models of the formation and evolution of bulges (see §5 below). Walterbos and Kennicutt also derived structural parameters for the disk and bulge that are consistent with the correlation between scale-lengths found for the larger sample of more distant disk galaxies by Courteau, de Jong and Broeils (1996). In terms of total optical light, the bulge-to-disk ratio of M 31 is about 40%.

Pritchet and van den Bergh (1996) emphasise that a *single* $R^{1/4}$-law provides a good fit to their derived V-band surface photometry (from star counts), with no bulge/halo dichotomy. The $R^{1/4}$ component is significantly flattened, with axial ratio of 0.55, which is similar to the value for the metal-poor halo of the Milky Way (Larsen and Humphreys 1994; Wyse and Gilmore 1989).

In contrast to the metal-poor halo of the Milky Way, which is apparently flattened by anisotropic velocity dispersions, the bulge of M31 has kinematics consistent with an isotropic oblate rotator, with mean rotational velocity of ~ 65 km/s and velocity dispersion of ~ 145 km/s (McElroy 1983), typical of external bulges (Kormendy and Illingworth 1982).

Thus although Baade identified the 'bulge' of M31, that is, field non-disk stars at distances up to 35kpc from the centre of M31, with 'Population II', similar to the Milky Way halo, the dominant tracers of the M31 bulge do not share the characteristics of classical Galactic 'Population II', being neither of low mean metallicity nor having little net rotation (see Wyse and Gilmore 1988 for further development of this point, in the context of thick disks).

There are around 200 confirmed globular clusters associated with M31 (e.g. Fusi Pecci *et al.* 1993). The distribution of their metallicities has a mean of around -1 dex, more metal-poor than the field stars, with a range of perhaps one dex on either side (e.g. Huchra, Brodie and Kent 1991; Ajhar *et al.* 1996). The inner, metal-rich clusters form a rapidly rotating system, while the outer metal-poor clusters have more classical 'hot' halo kinematics (e.g. Huchra 1993; see also Ashman and Bird 1993 for further discussion of sub-systems within the globular clusters). The overall globular cluster system has a projected number density profile that may be fit by a de Vaucouleurs profile (although the central regions fall off less steeply) with an effective radius of $\sim 4 - 5$ kpc (Battistini *et al.* 1993). This is more extended than the $R^{1/4}$ fit to the field stars. Thus in terms of kinematics, metallicity and structure, there may be evidence for a bulge/halo dichotomy in M31 if the halo is traced by the globular clusters and the bulge by field stars. Note that, although there are exceptions, to first order the spatial distributions of globular cluster systems and underlying galaxy light are similar (Harris 1991).

As seems to be case for any system studied in sufficient detail, the morphology of the very central regions of M31 is clearly complicated, with twisted isophotes (Stark 1977); gas kinematics which may trace a bar (e.g. Gerhard 1988); inner spiral arms (e.g. Sofue *et al.* 1994); two nuclei (Bacon *et al.* 1993) which may indicate a tilted, inner disk (Tremaine 1995). These phenomena have been modelled recently by Stark and Binney (1994) by a spherical mass distribution plus a weak prolate bar, with the bar containing one-third of the mass within 4 kpc (the corotation radius). The association of 'the bulge' with this bar, which one might be tempted to adopt by analogy with the Milky Way, is unclear.

Section 2.4 LMC

The LMC is the nearest barred galaxy, with the bar being offset from the kinematic and isophotal centre, and embedded in an extensive disk. A minor metal-poor old component of the LMC is seen in deep HST colour-magnitude data (Elson, Gilmore and Santiago 1997), but its kinematics and spatial distribution are not yet well known. There is a significant amount of new information concerning the variable star population of the LMC from the several microlensing experiments, in particular for the Long Period Variables, believed to have low-mass progenitors and hence trace older stellar populations, and RR Lyrae variables, traditional tracers of old, metal-poor populations. However, most of the information has yet to be analysed. There has been no kinematical analysis of the

LPVs since that of Hughes, Wood and Reid (1991), who found tentative indications of classical 'hot' halo kinematics. The old globular clusters of the LMC, against prejudice, have kinematics consistent with being in a rotating disk (e.g. Freeman 1993). Thus there is little evidence for a bulge or halo population in the LMC, except the observation that an old, metal-poor stellar population exists.

Section 2.5 General Properties of the Local Group Disk Galaxies

The diversity of properties of bulges, haloes and disks evident in the four largest disk galaxies in the Local Group is striking. The essential properties seem to be the following. The two latest type galaxies (M33, LMC) have no convincingly detected bulge, but both have at least some evidence for a small population of very old, metal-poor stars. Both have old, metal-poor globular clusters. The intermediate-type Milky Way Galaxy contains what can be termed both a halo - metal-poor, old, extended, narrow abundance distribution, containing globular clusters; and a bulge - metal-rich, mostly, and perhaps exclusively, fairly old, with a very broad metallicity distribution function, and extremely compact in spatial scale. The earlier-type M31 has a prominent and extended bulge, which is both quite metal-rich and fairly old, and has a broad abundance distribution function. The only evidence for a metal-poor old halo in M31 comes from its globular clusters, and its - very few - RR Lyrae stars and Blue Horizontal Branch stars. In all cases haloes are pressure supported systems, very unlike disks, though this is perhaps as much a definition as an observation.

Thus, while the Local Group Spiral galaxies have a definable Halo:Disk ratio, which is apparently rather similar for all three, only the two earlier types have a definable Bulge:Disk ratio, which is greater for M31 than for the Milky Way.

Section 3 : Low Redshift, Unresolved Bulges

§3.1 Bulges and Ellipticals

In the most simplified picture of galaxies, a galaxy consist of a bulge which follows an $R^{1/4}$ profile, and an exponential disk, while elliptical galaxies are simply the extension of bulges in the limit of bulge-to-disk ratio tending to infinity.

The picture has been complicated by the discovery that most intermediate luminosity ellipticals (classified from photographic plates) have significant disks (e.g. Bender, Doebereiner and Moellenhoff 1988; Rix and White 1990). These disks can be very difficult to detect, especially when seen face-on. Kormendy and Bender (1996) have recently proposed that ellipticals with 'disky' isophotes, which tend to be of lower luminosity than those with 'boxy' isophotes, are the natural extension of the Hubble sequence of disk galaxies.

Futhermore, many ellipticals show nuclear disks, either from their kinematics, or high-resolution imaging (e.g. review of de Zeeuw and Franx 1991). These disks are very concentrated towards the center, and are therefore different from disks in normal spiral galaxies. Sometimes these disks have an angular momentum vector opposite to that of the 'bulge' (e.g. IC 1459, Franx and Illingworth 1988), implying that the gas that formed the disk did not have its genesis in the stars of the 'bulge', but was accreted from elsewhere.

Notice, however, that some spiral galaxies also show evidence for these 'nuclear disks', including the Milky Way (Genzel *et al.* 1996), and the Sombrero galaxy (Emsellem *et al.* 1996).

HST observations confirm the similarity in some aspects of low-luminosity ellipticals and bulges. Most of these systems have "power law" profiles in their inner parts, with steep index (e.g. Faber *et al.* 1996). In contrast, most high-luminosity ellipticals show 'breaks' in their surface brightness in the inner regions, i.e. relatively sudden changes where the intensity profiles flatten. It is not clear yet what formation processes have caused these variations, although it has been suggested that the dynamical effects of massive black holes may be responsible (Faber *et al.* 1997).

These results suggest caution in the analysis of other data, as bulges are not necessarily the only important component near the center, and as the formation histories of many galaxies may have been quite different from each other. Indeed, it is clear that the central regions of most, if not all, galaxies contain something 'unusual' – even without the benefit of detailed HST images (e.g. note NGC 4314 in the Hubble Atlas, which is a barred galaxy with spiral arms in the center of the bar).

Beyond the very central regions, a systematic variation of surface brightness profile with bulge luminosity has been established, in that bulges in late type spiral galaxies are better fit by exponential profiles than by the de Vaucouleurs profile which is appropriate for early type spirals (e.g. Andredakis, Peletier and Balcells 1995; de Jong 1995; Courteau, de Jong and Broeils 1996). HST imaging of late type spirals is needed to determine better the structure of their bulges. Preliminary results indicate that a significant fraction of bulges in late type spirals have power law profiles in their inner parts (e.g. Phillips *et al.* 1996)

Much recent research into the properties of elliptical galaxies has demonstrated the existence of a 'fundamental plane' which characterises their dynamical state (e.g. review of Kormendy and Djorgovski 1989; Bender, Burstein and Faber 1993). It has also recently been demonstrated that the bulges of disk galaxies in the range S0–Sc (T0–T5) occupy the same general locus in this plane (Jablonka, Martin and Arimoto 1996). Further, these bulges have a similar Mg2 linestrength–velocity dispersion relationship to that of ellipticals, but with bulges offset slightly to lower linestrengths. This offset may be due to bulges having lower metallicity, or bulges having lower age. Contamination by disk light can produce a similar effect. Jablonka *et al.* argue in favour of a close connection between ellipticals and bulges. Balcells and Peletier (1994) find that bulges follow a colour–magnitude relationship similar to that of ellipticals, but that bulges have a larger scatter, and further bulges and ellipticals of the same luminosity do not have the same colours, but bulges are bluer; the offset is similar to that seen by Jablonka *et al.* in the strength of the magnesium index, but Balcells and Peletier interpret it as indicating a real, though complex, difference between bulges and ellipticals. In addition to the data noted above on the central parts of bulges, Balcells and Peletier (1994) find that the amplitude of radial colour gradients also varies systematically with bulge luminosity. They interpret their

results as consistent with bright bulges ($M_R < -20$) being similar to ellipticals (despite the colour zero-point offset) while faint bulges are perhaps associated with disks.

Figure 4 here

The potential well of the outer regions of disk galaxies is clearly dominated by dark matter, while the properties of dark matter haloes around elliptical galaxies are less well known (e.g. de Zeeuw 1995). How do properties of bulges scale with dark haloes? Figure 4 shows the ratio of bulge dispersion divided by the circular velocity of the halo (derived from rotation of tracers in the disk) against bulge-to-disk ratios. The square on the right represents elliptical galaxies, derived from models by Franx (1993) which assume a flat rotation curve. The triangle on the left corresponds to the inner regions of pure disks, as derived for a sample of Sa–Sc galaxies by Bottema (1993; it should be noted that the inner regions of disks are not 'cold', but warm). Bulges may be seen to lie on a rather smooth sequence between these two extreme points. This suggests that the bulges in galaxies with low bulge-to-disk ratios may have been formed as the same time as the disk, whereas bulges in galaxies with large bulge to disk ratios are so much hotter than the disk that it is more likely that they formed separately. More and better data would be valuable to improve the diagram.

§3.2 Bulges and Disks

Astronomical gospel declares that bulges are red, and disks are blue. This is generally presumed to be derived from studies of nearby bulges. Unfortunately, there are very few data on which these rather strong statements are based. The observations were difficult to do before the advent of CCD cameras, and have been lacking afterwards until very recently – perhaps because the problem was considered to be solved. Full two dimensional imaging is needed for accurate bulge/disk decomposition, and for exclusion of dusty areas, and large surveys with multicolour information are still rare. Notable exceptions are the recent studies of the colours of 'normal' spiral galaxies by de Jong (1995; de Jong 1996) and by Balcells and Peletier (1994; Peletier and Balcells 1996).

A relationship between bulges and disks is seen clearly in their colours. Figure 5 shows the colour of the disks, measured at two disk scale-lengths, against the colour of the bulges, measured at half the bulge effective radius, in the sample of Peletier and Balcells, which consists of luminous ($M_R \lesssim -21$) nearby disk galaxies, spanning the range S0–Sbc.

Figure 5 here

It is noticeable how large the colour range is for the bulges - almost as large as the range of colours for the disks. Furthermore, although some bulges are quite red, it is also clear that blue bulges exist, and also that red disks exist. The sample of de Jong (1996) includes the later morphological types of disk galaxies (Sc and Sd) and shows a similar relationship between the colours of bulge and inner disks. These data show that there is little support for sweeping statements such as 'bulges are red, and disks are blue'. Colour data for the 'hidden' disks in elliptical galaxies would be very interesting.

Further, the similarity in colour between inner disk and bulge has been interpreted as implying similar ages and metallicities for these two components, and an implicit evolutionary connection (de Jong 1996; Peletier and Balcells 1996). Given the difficulties of disentangling the effects of age and metallicity even with resolved bulges, any quantification of 'similar' must be treated with caution (see Peletier and Balcells who derive an age difference of less than 30%, assuming old populations with identical metallicities). We notice in passing that the ages of ellipticals have not been determined yet to high accuracy; measurements of various absorption linestrengths have been interpreted to indicate a wide range of ages of the central regions of ellipticals, with no correlation between age and luminosity (Faber *et al.* 1995), but this is far from rigourously established.

A close association between bulges and disks has been suggested by Courteau, de Jong and Broeils (1996), on the strength of a correlation between the scalelengths of the bulge and disk; they find that bulges have about one-tenth the scale-length of disks. This correlation shows considerable scatter, especially for earlier galaxies of type Sa, and relies upon the ability to measure reliably bulge scalelengths which are a small fraction of the seeing. More and better data are anticipated.

§3.3 Bulges in formation at $z < 0.1$?

A few exceptional systems locally are candidates for young bulges. It is clear that gravitational torques during interactions can act to drive gas to the central regions (e.g. Mihos and Hernquist 1994), where it may form stars, and which may, depending on the duration of star formation and of the interaction, be heated into a bulge. Schweizer (1990) discusses local disk galaxies with blue bulges, presenting them as evidence for recent bulge-building in this manner. These galaxies include NGC 5102, an S0 galaxy with a bluer bulge than disk, and strong Balmer absorption lines in its central regions. Classic merger remnants such as NGC 7252 are forming disks in their central parts, implying that these galaxies may evolve into S0's, or early type spirals (e.g., Whitmore *et al.* 1993)

A more dramatic example of gas-rich mergers is Arp 230, which shows classical shells in the bulge component, and a young disk rich in gas, as displayed in Figure 6 (D. Schmininovich and J. van Gorkom private communication).

Figure 6 here

Section 4 : High Redshift Bulges

Direct searches for the progenitors of local bulges may be made by the combination of statistically complete redshift surveys of the field galaxy population, combined with photometric and especially with morphological data. As an example, the I-band-selected CFHT redshift survey contains galaxies out to redshifts of order unity, and may be analysed in terms of the evolution of the luminosity function of galaxies of different colours, presumed to correlate with morphological type (Lilly *et al.* 1995). These data are consistent with very little evolution in the luminosity function of the 'red' galaxies, over the entire redshift range $0 < z < 1$, and substantial evolution in the 'blue' galaxies' luminosity function, with the colour cut dividing the sample into 'blue' and 'red' taken as the rest-frame colour

of an unevolving Sbc galaxy. This lack of evolution for red galaxies may be interpreted as showing that the stars of bulge-dominated systems – the 'red' galaxies – were already formed at redshifts greater than unity, corresponding to a look-back time of greater than half of the age of the Universe, or 5–10 Gyr (depending on cosmological parameters).

The high spatial resolution of the Hubble Space Telescope allows morphological information. Schade *et al.* (1995) obtained HST images for a subset (32 galaxies in total) of the CFHT redshift survey, mostly 'blue' galaxies with $z > 0.5$. They found, in addition to the 'normal' blue galaxies with exponential disks and spiral arms and red bulge-dominated galaxies, a significant population of high luminosity ($M_B < -20$) 'blue nucleated galaxies', with large bulge-to-disk ratio (B/T $\gtrsim 0.5$) – could these be bulges in formation, at lookback times of ~ 5 Gyr? Small number statistics notwithstanding, most of the 'BNG' are asymmetric and show some suggestions of interactions. Schade *et al.* (1996) found similar results for a larger sample, using just CFHT images for morphological classification, and confirmed that 'red' galaxies tend to have high bulge-to-disk ratios.

Extending these results to even higher redshifts, and hence studies of progenitors of older present-day bulges, has been achieved by the identification of a sample of galaxies with $z \gtrsim 3$ based on a simple colour criterion that selects systems with a Lyman-continuum break, superposed on an otherwise flat spectrum, redshifted into the optical (e.g. Steidel *et al.* 1996a,b). Ground-based spectroscopy of 23 high-redshift candidates provided 16 galaxies at $z > 3$ (Steidel *et al.* 1996b). The observed optical spectra probe the rest-frame 1400-1900Å UV, and provide a reasonable estimate of the reddening and hence dust content, and of the star-formation rate. The systems are inferred to be relatively dust-free, with the extinction at ~ 1600Å typically ~ 1.7mag, corresponding to an optical reddening in the galaxies' rest-frame of $E(B-V) \sim 0.3$mag. Whether the low dust content is a selection effect, perhaps due to fortuitous observing line-of-sight, or is a general feature of these high-redshift galaxies is not clear. The co-moving space density of these systems is large – of order half that of bright ($L > L_*$) galaxies locally, suggesting that not too many of them can be hidden. The star formation rates, assuming a solar neighbourhood IMF, are typically $\sim 10 \ M_\odot$/yr. There are interstellar absorption lines due to various chemical species; these lines may be interpreted as indicative of gas motions in a gravitational potential of characteristic velocity dispersion of ~ 200km/s, typical of normal galaxies today.

Morphological information from optical HST images (Giavalisco *et al.* 1996) for 19 Lyman-break candidates, of which 6 have confirmed redshifts, show that in the rest-frame UV (1400–1900Å) these systems are mostly rather similar, in contrast to the wide range of morphological types seen at lower redshifts, $z \sim 1$, discussed above. Further, the typical $z \sim 3$ galaxy selected this way is compact, at least in the UV, and has a half-light radius of ~ 2 kpc, reminiscent of present-day bulges in the optical. Some of these galaxies show faint surrounding emission which could be interpreted as 'disks'. The star-formation rates inferred from the spectra build the equivalent of a bulge – say $10^{10}M_\odot$ – over a few Gyr, which spans the redshift range from $1 \sim z \sim 4$. Similar results are obtained from $z > 3$ samples derived from the Hubble Deep Field (Steidel *et al.* 1996a), and for one galaxy

at a redshift of $z = 3.43$, the central regions of which even fit a de Vaucouleurs profile (Giavalisco *et al.* 1995).

Thus there is strong evidence that some (parts of some) bulges are formed at $z \gtrsim 3$. However, it is hard to draw definite conclusions about all bulges on the basis of these results, because the observations at these redshifts can be biased. If, for example, half of bulges form at $z \lesssim 0.5$, then we would simply not observe those at higher redshifts. At higher and higher redshifts, we would simply be selecting older and older bulges. Our conclusions would become strongly biased. This is very similar to the bias for early type galaxies discussed by van Dokkum and Franx (1996).

Section 5 : Formation Scenarios
5.1 Are Bulges Related to their Haloes?

Analyses of globular cluster systems in external galaxies conclude that they are more metal-poor in the mean than is the underlying stellar light, at all radii in all galaxies (Harris 1991). It is worth noting that the Milky Way is sometimes considered an anomaly here, in that the metallicity distribution function for the (metal-poor, aka halo) globular cluster system is not very different from that of field halo stars, with differences restricted to the wings of the distributions (e.g. Ryan and Norris 1991). It is important to note however that this comparison is done in the Milky Way at equivalent halo surface brightness levels well below those achievable in external galaxies. The higher-surface brightness part of the Milky Way, that part appropriate to compare to similar studies in other galaxies, is the inner bulge. As discussed above, the metallicity there is well above that of the globular clusters. The Milky Way is typical. More importantly, this (single) test suggests the possibility that *ALL* spiral galaxies which have globular cluster systems have a corresponding field halo, which in turn is systematically more metal-poor and extended than is the more metal-rich, observable, bulge.

If this is true, the Local Group galaxies are typical, and the concept of 'stellar halo' must be distinguished from that of 'stellar bulge'. Additionally, while haloes seem ubiquitous, they are always of low luminosity, and seem generally more extended than bulges. Bulges are not ubiquitous, being found in earlier type galaxies, and cover a very wide range of luminosities.

What is the evolutionary relationship, if any, between bulges and haloes? The Milky Way is an ideal case to study this, since it has both bulge and halo. We noted above that the bulge is more metal-rich, and possibly younger than the halo. What of its dynamics?

Fig 7 here

In the Milky Way the bulge stars do show significant net rotation, (e.g. Ibata and Gilmore 1995b; Minniti *et al.* 1995) but the very concentrated spatial distribution of these stars leads to low angular momentum orbits. Indeed, the angular momentum (per unit mass) distribution of the bulge is very similar to that of the stellar halo, and very different from that of the disk (Wyse and Gilmore 1992; Ibata and Gilmore 1995b); see Figure 7. As discussed below, this is suggestive of the ELS scenario, with the bulge being the central

20

regions of the halo, but formed with significantly more dissipation. Further, the available estimates of the masses of the stellar halo and bulge give a ratio of $\sim 1 : 10$, which is (coincidently?) about the ratio predicted by models in which the bulge is built-up by gas loss from star-forming regions in the halo (e.g. Carney, Latham, & Laird 1990; Wyse 1995). The real test of this model is determination of the *rate* of formation, and chemical enrichment, of the stars in each of the halo and bulge. This is feasible, and requires good data on element ratios (e.g. Wyse and Gilmore 1992).

5.2 Accretion/Merging

§5.2.1 Destruction of Disks by Mergers

The current paradigm of structure formation in the Universe is the hierarchical clustering of dominant dissipationless dark matter; galaxies as we see them form by the dissipation of gas into the potential wells of the dark matter, with subsequent star formation (e.g. Silk and Wyse 1993). The first scales to collapse under self-gravity are characteristic of dwarf galaxies, and large galaxies form by the merging of many smaller systems. The merging rate of the dissipationless dark haloes is reasonably straightforward to calculate (e.g. Lacey and Cole 1993). There are unfortunately many badly-understood parameters involved in the physics of gaseous heating/cooling and star formation, which determine how the baryonic components evolve. In the absence of understanding, the naive separation of different stellar components of galaxies is achieved by the following prescription (Baugh, Cole and Frenk 1996; Kauffmann 1996) – star formation occurs in disks, which are destroyed during a merger with a significantly larger companion (the meaning of 'significant' being a free parameter to be set by comparison with observations). In such a merger all the extant 'disk' stars are re-assigned to the 'bulge', the cold gas present is assumed to be driven to the center and fuel a burst of star formation, and a new disk is assumed to grow through accretion of intergalactic gas. Ellipticals are simply bare bulges, more likely in environments that prevent the subsequent re-accretion of a new disk – environments such as clusters of galaxies (e.g. Gunn and Gott 1972). One consequence (see Kauffmann 1996) of this prescription is that late-type spirals, which have a large disk-to-bulge ratio, should have older bulges than do early-type spirals, since to have a larger disk the galaxy must have been undisturbed and able to accrete gas for a longer time. This does *not* appear compatible with the observations discussed above. Bulge formation is highly likely to be more complex than this simple prescription.

§5.2.2 Accretion of Dense Stellar Satellites

The central regions of galaxies are obvious repositories of accreted systems, being the bottom of the local potential well, provided the accreted systems are sufficiently dense to survive tidal disruption while sinking to the centre (e.g. Tremaine, Ostriker and Spitzer 1975). Should the accreted systems be predominately gaseous, then the situation is simply that described by Eggen, Lynden-Bell and Sandage (1962), with the chemical evolution modified to include late continuing infall. [It is worth noting that late infall of gas *narrows* resulting chemical abundance distribution functions (e.g. Edmunds 1990), and at least the Milky Way bulge has an observed very broad distribution.] We now consider models of bulge formation by accretion of small stellar systems.

As discussed above, the mean metallicity of the bulge is now reasonably well-established at [Fe/H]~ -0.3 dex (McWilliam and Rich 1994; Ibata and Gilmore 1995), with a significant spread below -1 dex, and above solar. Thus satellite galaxies that could have contributed significantly to the bulge are restricted to those of high metallicity. Given the fairly well-established correlation between mean metallicity and galaxy luminosity/velocity dispersion (e.g. Bender, Burstein and Faber 1993; Zaritsky, Kennicutt and Huchra 1994; Lee *et al.* 1993) only galaxies of luminosity comparable to the bulge can have been responsible. That is, one is immediately forced to a degenerate model, in which most of the stellar population of the bulge was accreted in one or a few mergers, of objects like the Magellanic Clouds, or the most luminous dwarf spheroidals (dSph). Since the metallicity distribution of the Bulge is very broad, significantly broader than the solar neighbourhood, a compromise model is feasible, in which only the metal-poor tail of the bulge abundance distribution function has been augmented by accretion of lower luminosity satellite galaxies. Quantification of this statement awaits more robust measurement of the tails of the bulge metallicity distribution function, and of appropriate element ratios.

Limits on the fraction of the bulge which has been accreted can be derived from stellar population analyses, following the approach utilised by Unavane, Wyse and Gilmore (1996) concerning the merger history of the Galactic halo. The Sagittarius dwarf spheroidal galaxy was discovered (Ibata, Gilmore and Irwin 1994) through spectroscopy of a sample of stars selected purely on the basis of colour and magnitude to contain predominantly K giants in the Galactic bulge. After rejection of foreground dwarf stars, the radial velocities isolated the Sagittarius dwarf galaxy member stars from the foreground bulge giants. The technique (serendipity) used to discover the Sagittarius dSph allows a real comparison between its stellar population and that of the bulge. Not only the radial velocities distinguish the dwarf galaxy, but also its stellar population – as seen in Figure 8 here (taken from Ibata et al. 1994), **all** giant stars redder than $B_J - R \gtrsim 2.25$ have kinematics that place them in the low velocity-dispersion component *i.e.* in the Sagittarius dwarf. This is a real quantifiable difference between the *bulge* field population and this, the most metal-rich of the Galactic satellite dwarf spheroidal galaxies.

Figure 8 here

Further, the carbon star population of the bulge can be compared with those of typical extant satellites. In this case there is a clear discrepancy between the bulge and the Magellanic Clouds and the dSph (Azzopardi and Lequeux 1992), in that the bulge has a significantly lower frequency of carbon stars.

Thus although accretion may have played a role in the evolution of the bulge of the Milky Way, satellite galaxies like those we see around us now cannot have dominated. However, accretion is the best explanation for at least one external bulge – that of the apparently normal Sb galaxy NGC 7331, which is counter-rotating with respect to its disk (Prada *et al.* 1996). It should also be noted that for S0 galaxies – those disk galaxies that in theory have suffered the most merging – Kuijken, Fisher and Merrifield (1996) have completed a survey for counter-rotating components in the disks, and find that only 1% of S0 galaxies contain a significant population of counter-rotating disk stars. This is a

surprisingly low fraction, and suggests some caution prior to adopting late merger models as a common origin of early-type systems.

5.3 Disk–Bars–Bulges etc

Recall that the broad-band colour distributions of disk galaxies show smooth continuity across the transition between disk and bulge. In the mean there is approximate equality between the colours of the inner disk and the bulge in any one galaxy (de Jong 1996; Peletier and Balcells 1996). These data may be interpreted as showing similar mean age and metallicity for inner disk and bulge (de Jong 1996; Peletier and Balcells 1996), but the degeneracy of age and of metallicity on the colours of stellar populations cause uncertainties. Courteau, de Jong and Broeils (1996) find further that the scale-lengths of disk and bulge are correlated, and argue that this relationship implies that the bulge formed via secular evolution of the disk. In principle this is possible, if disks are bar-unstable, and bars are themselves unstable, and very significant angular-momentum transport is feasible.

The secular evolution of collisionless stellar disks has been studied in some detail recently, in particular through three-dimensional N-body simulations (Combes *et al.* 1990; Raha *et al.* 1991; see Combes 1994 and Pfenniger 1993 for interesting reviews). These simulations demonstrated that not only are thin disks often unstable to bar formation, but bars themselves can be unstable, in particular to deformations out of the plane of the disk, perhaps leading to peanut-shaped bulges. The kinematics of stars in peanut bulges lends some observational support for the association of peanut-bulges with bars (Kuijken and Merrifield 1995). Thus stars initially in the inner disk end up in the bulge, providing a natural explanation for the continuity observed in the properties of the stellar populations in disks and in bulges.

Merritt and Sellwood (1994; see also Merrifield 1996) provided a detailed description of the physics of instabilities of stellar disks. They demonstrate that the buckling instability of the stellar bar that produces a 'peanut bulge' (Combes *et al.* 1990; Raha *et al.* 1991) is a collective phenomenon, similar to a forced harmonic oscillator. Thus the instability involves the bar in general, not only stars on special resonant orbits, as had been earlier proposed (e.g. Combes *et al.* 1990). Not all instabilities form 'peanuts', which is just as well for this class of model for bulge formation, since, while box/peanut bulges are perhaps fairly common, comprising 20% of galaxies (Shaw 1987), the subset of these which rotate on cylinders is small (e.g. Shaw 1993, and refs therein). Relevant photometric studies show that the light in a peanut bulge is additional to that in a smooth underlying disk, not subtracted from it (e.g. Shaw, Dettmar and Bartledress, 1990; Shaw 1993), rather weakening the case for these models.

The extant simulations of bar-instabilities also find that a very small mass concentration can destroy the bar. Such a mass concentration is very likely, since inflow, driven by gravitational torques, is probable after a bar is formed. Hasan and Norman (1990) suggested that a sufficiently large central mass concentration could eventually destroy the bar. Norman, Sellwood and Hasan (1996) used 3-D N-body simulations to follow the evolution of a bar-unstable disk galaxy, and attempt to incorporate the effects of gas inflow by

allowing the growth of a very centrally-concentrated component. Indeed, in time the fraction of material in this central component is sufficient to destroy the bar, fattening it into a 'bulge-like' component. Bulges may be built up by successive cycles of disk instability–bar-formation–bar-dissolution (Hasan, Pfenniger and Norman 1993). The timescales and duty-cycles are not clear. Some simulations (e.g. Friedli 1994) find that as little as 1% of the mass in a central component is sufficient to dissolve a bar. This is a potential problem, as Miller (1996) points out, since the fact that one observes bars in around 50% of disk galaxies means that bars cannot be fragile. A numerical example supporting Miller's important point is provided by Dehnen (1996) who finds that his bar is stable even with a cuspy density profile in the underlying disk; the simulations are clearly not yet mature.

A further potential problem with the general applicability of this scenario of bulge formation is the different light profiles of bars in galaxies of different bulge-to-disk ratio – early-type disk galaxies have bars with flat surface density profiles (e.g. Noguchi 1996; Elmegreen *et al.* 1996), while late-type galaxies have bars with steeper surface brightness profiles than their disks. The Courteau *et al.* correlation, that bulge scale-lengths are around 1/8 that of disks, was found for a sample of late-type galaxies. In this scenario the colour of a bar should also be the same colour as its surrounding disk, so that the subsequent bulge is the same colour as the disk. While colours of bars are complicated by dust lanes and associated star formation, barred structures are often identified by means of colour maps (e.g. Quillen *et al.* 1996).

Specific counter-examples to models whereby the bulge forms through secular evolution of the inner disk, are the high luminosity but low surface brightness disk galaxies which have apparently 'normal' bulges (e.g. surface brightnesses and scale-lengths typical of galaxies with high surface brightness disks), such as Malin I (McGaugh, Schombert and Bothun 1995) that clearly could not have formed by a disk-instability.

Dissipationless formation of bulges from disks suffers yet a further problem, in that the phase space density of bulges is too high (Ostriker 1990; Wyse 1997). This also manifests itself in the fact that the spatial densities of bulges are higher than those of inner disks. Thus one must appeal to dissipational processes to form bulges, such as gas flows. The presence of colour gradients in some external bulges would support a dissipative collapse with accompanying star formation (e.g. Balcells and Peletier 1994). Indeed, Kormendy (1993) has argued that many 'bulges' are actually inner extensions of disks, formed through gas inflow from the disk, with later *in situ* star formation. This complicates the interpretation of the similarity between the colours of bulges and inner disks, which was a natural product of a stellar-instability to form bulges from disk stars. One should note also that should bulges indeed not be formed at high redshift, then dissipation is also implicated in the production of the high spatial densities of their central regions.

It is also important to note that the term 'bar' is used no less generically than is the term 'bulge'. There is a fundamental, and rarely clarified, difference between a detectable perturbation to the luminosity distribution, and a substantial $m = 2$ perturbation to the galactic gravitational potential. Inspection of the delightful pictures in the Carnegie

Atlas of Galaxies suggests a continuum of structures, with all degrees of symmetry and asymmetry (ie. $m = 1, 2, ...$) and relative amplitudes. When is a bar fundamentally more than the region where spiral arms meet the centre? More importantly for the continuing debate about the centre of the Milky Way, is it true that ALL these structures are seen in the cold disks only? Is there such a thing as a bar-bulge?

Section 6: Conclusions

In the Local Group, all spiral galaxies, and probably all disk galaxies, have an old, metal-poor, spatially-extended stellar population which we define to be a stellar halo. These seem to be the first stars formed in what would later become the galactic potential, though the possibility of later accretion of a minor fraction remains viable. The bulges of Local Group spiral galaxies are more diverse in properties, ranging from the very luminous, intermediate metallicity and very spatially-extended bulge of M31, through the intermediate luminosity, centrally-concentrated, bulge of the Milky Way, to no firm detection of a bulge in M33.

In general, well studied bulges are reasonably old, have a near-solar mean abundance, though importantly with a very wide abundance distribution function, and are consistent with isotropic oblate rotator models for their kinematics, in which the basic support is provided by random motions, and the flattening is consistent with additional rotational effects. Given these properties, bulges are most simply seen as the more dissipated descendents of their haloes.

However, diversity is apparent: all bulges of disk galaxies are not old, super-metal-rich and simply small elliptical galaxies. This is not to say that such systems do not exist, but that bulges are heterogeneous. Higher luminosity bulges seem to have a closer affinity to ellipticals, while lower luminosity bulges prefer disks. But even this statement does not apply to all the properties of the stellar populations of bulges.

This diversity, together with the surprisingly limited database available concerning the photometric, structural, and kinematic properties of bulges, preclude firm conclusions. Much new and much needed data are about to become available. It will be interesting to see if the next review on 'Bulges' will actually be entitled 'Disks and Ellipticals'.

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FIGURE CAPTIONS

Figure 1: An optical image of the central Galaxy, adapted from that published by Madsen and Laustsen (1986). The field covered is $70° \times 50°$. The Galactic Plane is indicated by the horizontal line, and the Galactic centre by the cross in the centre of the image. Also shown is an outline of the COBE/DIRBE image of the Galactic centre (smooth solid curve, Arendt *et al.* 1994), an approximate outline of the Sagittarius dSph galaxy (complex curve, from Ibata *et al.* 1997), with the four Sgr dSph globular clusters identified as asterisks, Baade's Window (heavy circle below the centre), the field of the DUO microlensing survey, which contains some of the other microlensing fields (solid square, overlapping the Sgr dSph rectangle;Alard 1996), the four fields for which deep HST colour-magnitude data are available (open squares, near Baade's Window), and the six fields surveyed for kinematics and metallicity by Ibata and Gilmore (1995a,b: black/white outline boxes). The location of Kepler's supernova is indicated as a circle, north of the Plane. Other features of relevance include the extreme extinction, preventing optical/near-IR low resolution observations of the bulge within a few degrees of the Plane, and the pronounced asymmetry in the apparent bulge farther from the Plane. The dust which generates the apparent peanut shape in the COBE/DIRBE image is apparent. The asymmetry at negative longitudes north of the Plane, indicated by a large dotted circle, is the Ophiuchus star formation region, some 160pc from the Sun. The Sagittarius spiral arm contributes significantly at positive longitudes in the Plane.

Figure 2: Chemical abundance distribution functions, normalized to unity, derived by Wyse and Gilmore (1995) except where noted. The distributions are, from top to bottom, the Solar neighbourhood stellar halo (Laird *et al.* 1988); the outer Galactic bulge (Ibata and Gilmore 1995b), truncated by them at solar metallicity; the younger stars of the solar neighbourhood; a volume-complete sample of local, long-lived stars; a volume-complete sample of local thick-disk stars; the column-integral through the disk abundance distribution for the sum of the long-lived thin disk and the thick disk.

Figure 3a,b: HST WFPC2 Colour-magnitude data for the Galactic Bulge, for the field at $(l, b) = (3.6, -7)$ identified in Fig 1 above, from the Medium Deep Survey. The left hand panel, Fig 3a, shows the data. Overlaid, from a by-eye fit, is a 12 Gyr isochrone for metallicity [Fe/H] $= -0.25$, from Bertelli etal (1994), together with a range of other ages plotted to one side, to illustrate the precision required, and the need for independent determinations of extinction at each point. The right hand panel, Fig 3b, shows the mean line through the data, excluding extreme points, together with the ridge line from similar HST data for the globular cluster 47 Tucanae (Santiago, Elson, and Gilmore 1996), arbitrarily offset to match the mean line.

Figure 4: a) The central velocity dispersion of stellar tracers, σ, against dark halo circular velocity, v_c. Open symbols are bulges, closed symbols are ellipticals. Circular velocities for the ellipticals are derived from models, as described by Franx (1993). (b) The ratio of velocity dispersion in the bulge to dark halo circular velocity, σ/v_c, taken from Franx (1993), plotted as a function of bulge-to-disk ratio, for the entire range of Hubble Type.

The triangle at left is valid for the inner regions of pure disks, the square at right for ellipticals. Note that systems with low B/T have kinematics almost equal to those of inner disks.

Figure 5: The correlation between bulge colour and the colour of the disk of the same galaxy, for the data of Peletier and Balcells (1996). Note that bulges are more like their disk than they are like each other, and the very wide range of colours evident.

Figure 6: An optical image of Arp 230, with overlaid HI contours. This galaxy shows evidence for shells in its outer bulge, indicating a recent substantial accretion event, and also has a young gas-rich disk (D. Schmininovich and J. van Gorkom private communication).

Figure 7: Cumulative distribution functions of specific angular momentum for the four major Galactic stellar populations. The solid curve is the distribution for the bulge, from Ibata and Gilmore (1995b). The other curves are taken from Wyse and Gilmore (1992): the dashed-dotted curve represents the halo, the dotted curve represents the thick disk, and the dashed curve represents the thin disk. It is clear that the halo and bulge are more like each other than they are like the disk components.

Figure 8: Heliocentric radial velocities of the sample of stars observed by Ibata, Gilmore and Irwin (1994), towards $\ell = -5°$, $b = -12°$, $-15°$, and $-20°$. The stars with velocities less than about 120km/s are predominately bulge K giants. Those with velocities between about 120km/s and 180km/s are members of the Sagittarius dwarf Spheroidal galaxy, which was discovered from this figure. Note the real difference between the colour distributions of bulge and Sgr members. Thus, the bulge cannot be built up by merger of several galaxies like the Sgr dwarf.
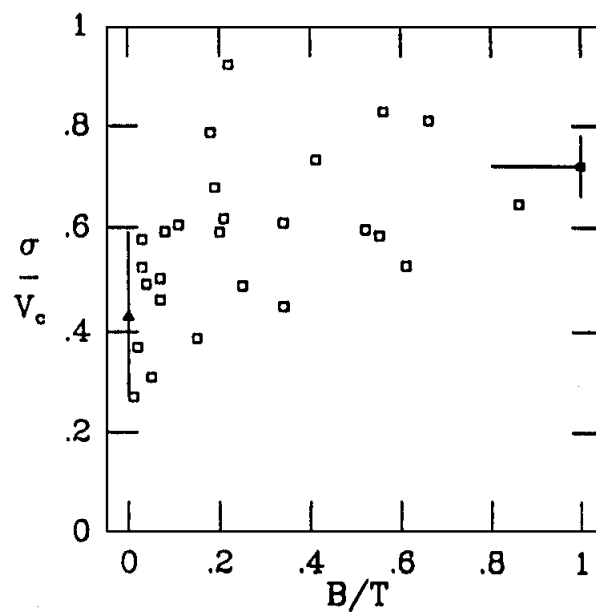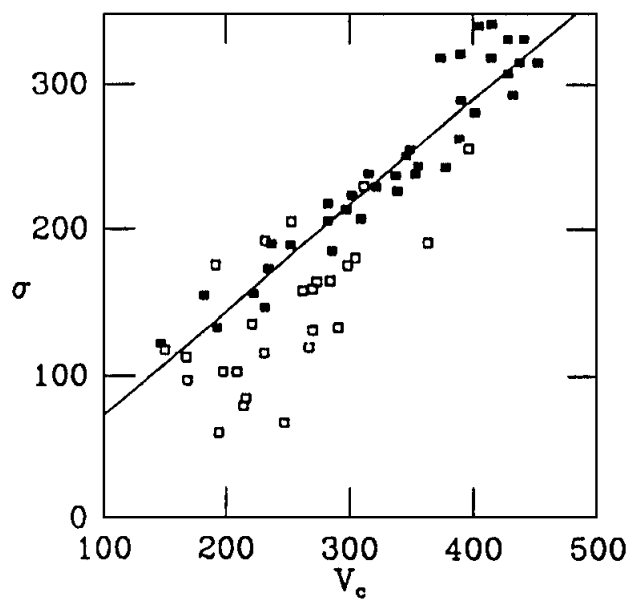
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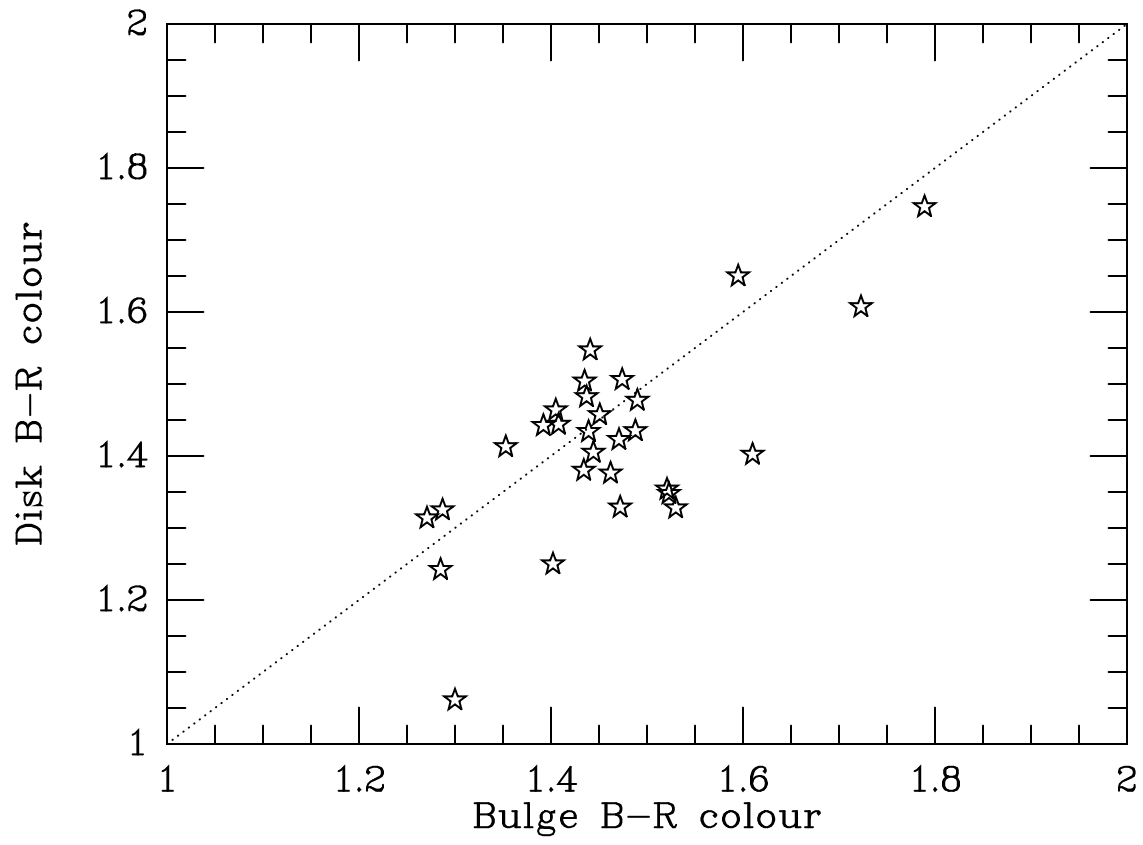
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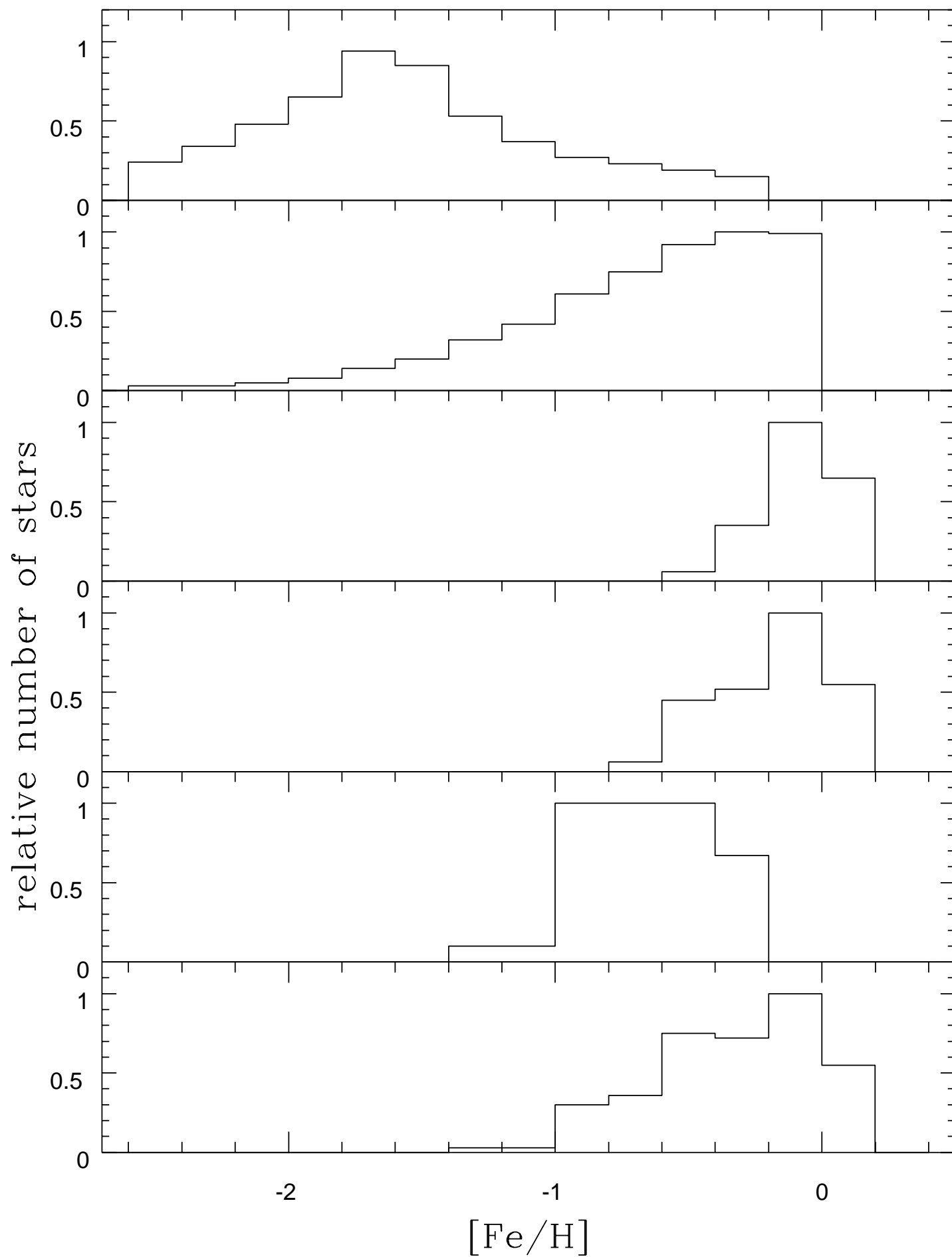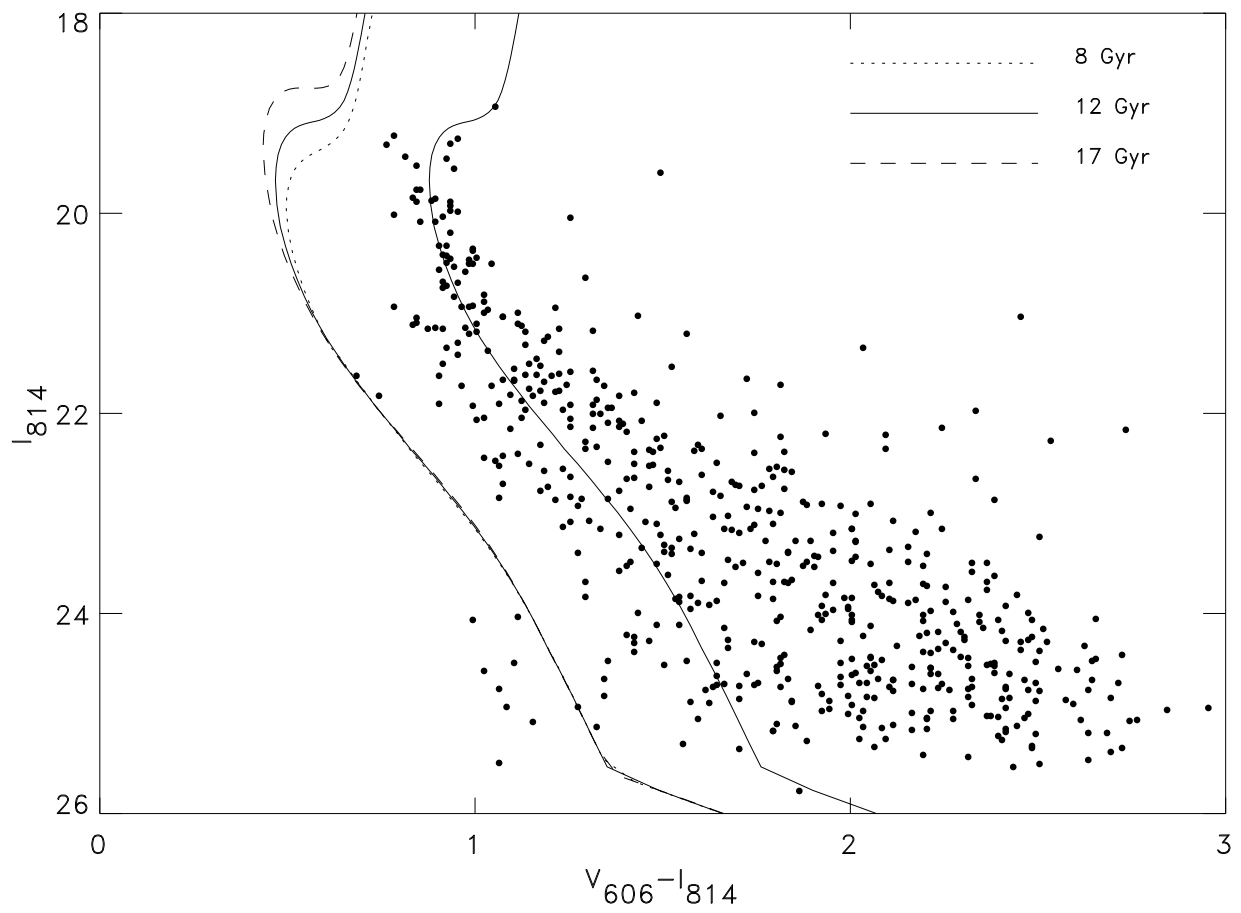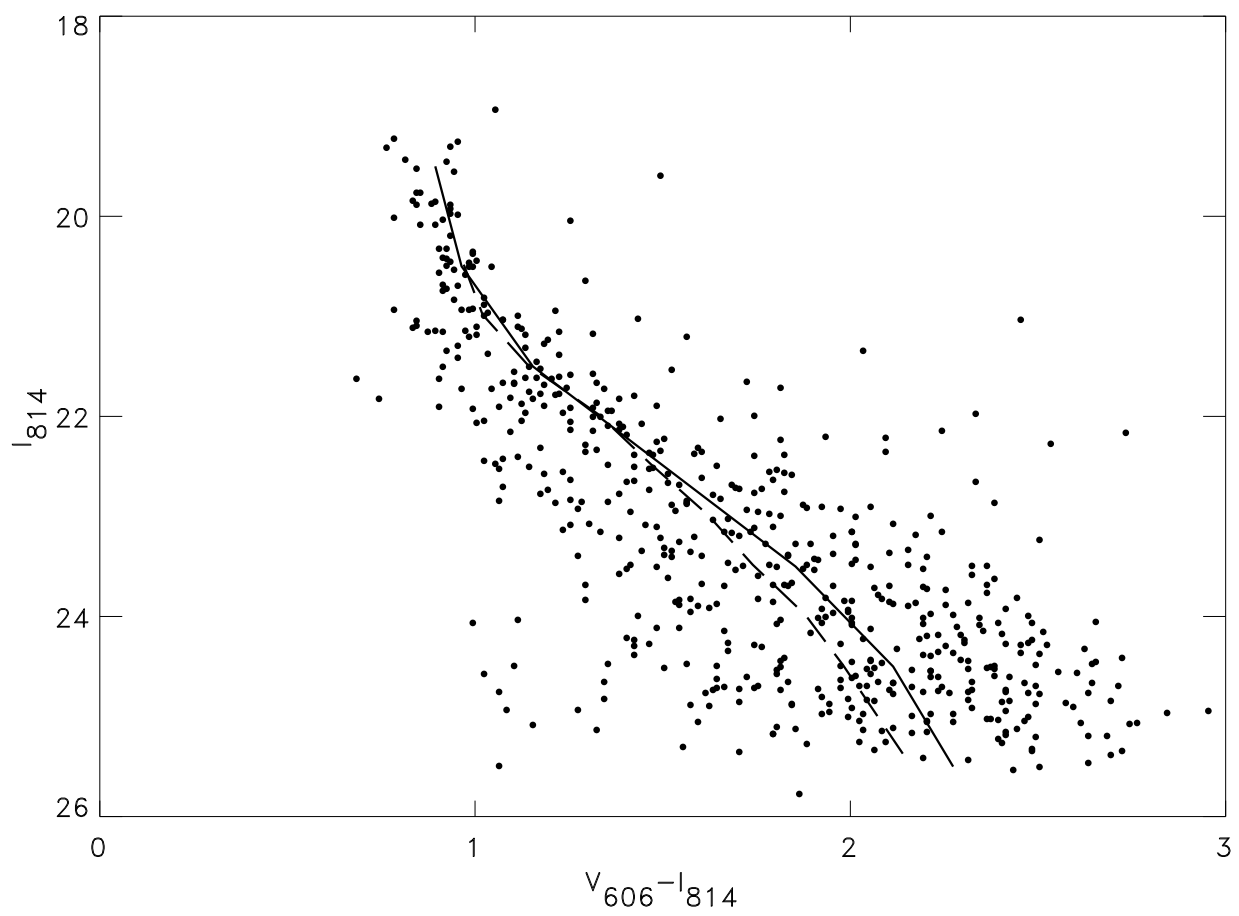
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